

# EOS MLS observations of dehydration in the 2004-2005 polar winters

C. Jiménez,<sup>1</sup> H. C. Pumphrey,<sup>1</sup> I. A. MacKenzie,<sup>1</sup> G. L. Manney,<sup>2,3</sup> M. L. Santee,<sup>2</sup>  
M. J. Schwartz,<sup>2</sup> R. S. Harwood,<sup>1</sup> and J. W. Waters<sup>2</sup>

**Abstract.** Observations of water vapour and temperature from the Earth Observing System Microwave Limb Sounder are used to study dehydration in the 2004 and 2005 polar vortices. Significant differences were found for the Antarctic winters, with the 2005 vortex colder and more extensively dehydrated. For the 2005 winter water vapour reductions were observed from mid-June, coincident with a decrease in temperatures, extending vertically between  $\sim 12$ -21 km. Reductions of up to  $\sim 3$  ppmv in water vapour were recorded a month later. Permanent dehydration was apparent between  $\sim 15$ -20 km, where 3 months later the temperature recovery was not followed by a recovery in water vapour. The 2004-2005 Arctic winter was unusually cold, but only one single event of depleted water vapour at the end of January was linked to ice formation. For this event, a reduction of up to  $\sim 0.5$  ppmv was observed over Spitsbergen between  $\sim 12$ -20 km.

## 1. Introduction

Reduction of water vapour in the lower stratosphere occurs in the polar winters when temperatures are sufficiently low to freeze the water vapour. If polar stratospheric clouds formed from the ice particles sediment to lower altitudes, the removal of water vapour is permanent and irreversible loss of water vapour occurs. This is referred to as dehydration and is a common feature of the Antarctic winters [e.g. *Kelly et al.*, 1989; *Stone et al.*, 2001; *Nedoluha et al.*, 2002]. In the Arctic higher temperatures make episodes of water vapour reduction more sporadic, though some events have been observed in cold winters [e.g. *Fahey et al.*, 1990; *Pan et al.*, 2002; *Herman et al.*, 2003].

The Earth Observing System (EOS) Microwave Limb Sounder (MLS), launched 15 July 2004, is an advanced follow on to the Upper Atmosphere Research Satellite (UARS) MLS instrument [*Waters et al.*, 2006]. It measures a suite of different geophysical products with better temporal and spatial coverage than UARS MLS. Although dehydration was studied from UARS MLS observations [e.g. *Stone et al.*, 2001], because of yaw manoeuvres and data gaps a whole winter period was never

---

<sup>1</sup>School of GeoSciences, The University of Edinburgh, Edinburgh, UK

<sup>2</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena

<sup>3</sup>Also at Department of Physics, New Mexico Institute of Mining and Technology

captured. Here we use EOS MLS data to provide a first view of the water vapour polar processes for the winters already observed by EOS MLS.

The version v1.5 MLS water vapour and temperature products were used to analyse the Antarctic late 2004 and the 2005 winters and the 2004-2005 Arctic winter. For single profiles in the lower stratosphere the water vapour estimated precision is  $\sim 0.1$  ppmv, vertical resolution  $\sim 4$  km, and horizontal resolution  $\sim 250$  km. Preliminary comparisons show a small positive bias of 5-10% with some other datasets. For temperature the horizontal resolution is  $\sim 200$  km, while the estimated precision is  $\sim 0.3$ - $0.5$  K, and the vertical resolution in the lower stratosphere ranges from  $\sim 7$  km (100 hPa) to 4 km (31-6.8 hPa). Initial comparisons suggest a warm bias of 1-2 K in the lower stratosphere. Further information and early validation results can be seen in [Froidevaux *et al.*, 2006].

## 2. The 2004 and 2005 Antarctic Winters

Figure 1 shows the evolution of MLS water vapour and temperature averaged in the vortex region for the late 2004 and 2005 winters. UK Met Office (MO) analyses were used to interpolate from pressure levels to isentropic surfaces and to derive scaled potential vorticity values (sPV) [Manney *et al.*, 1994]. The altitudes given in the figure are based on typical mid winter vortex geopotential heights, and will be used in the remaining text and figures to relate potential temperature to approximated heights. An sPV value of 1.3 was used to define the vortex edge;  $\sim 500$  profiles were averaged per day. Extensive dehydration can be observed in both winters, though there are clear differences for the time periods that can be compared. The differences seem to be qualitatively consistent with a colder 2005 winter corresponding to a more dehydrated polar vortex.

In Figure 2 the minimum and vortex-averaged water vapour and temperature values are plotted at some isentropic surfaces. Note that due to the limited vertical resolution of the measurements the values plotted at these levels are not completely independent. For a more representative value, an average of the three smallest values is plotted instead of just the minimum value. An approximated frost point temperature is calculated at each level by using the vortex-averaged water vapour, temperature and pressure. Clear differences can be observed between the coincident periods in 2004 and 2005. Dehydrated air can be observed from 340 to 560 hPa ( $\sim 12$ - $21$  km) for the 2005 winter, while for 2004 there is no signs of dehydration at or above 520 K. The lack of dehydration at this level seems atypical, as also noted by [Santee *et al.*, 2005], but firmer conclusions cannot be drawn as the data do not cover the beginning of the winter.

For the 2005 winter, the 560 K ( $\sim 21$  km) surface shows good correspondence between temperature below the frost point and the duration of the gas phase reduction. Although this seems to be an indication that the initial water vapour decrease at this altitude was reversible, it can also be related to the descent of moister air from above. At lower levels, there is also good consistency in timing between the reductions in temperature and water vapour, but the recovery in temperature is not followed by a recovery in water vapour, indicating irreversible removal of water from the gas phase. For most of the isentropic surfaces the water vapour reductions start from mid-June, though at 360 and 340 K ( $\sim 13$  and  $\sim 12$

km) the drop in water vapour happens later in July, in agreement with a later appearance of frost point temperatures. The timing of this onset fits well with the 1992 observations from UARS MLS [Stone *et al.*, 2001], though it should be noted that there seems to be significant inter-annual variation in the timing of this onset [Nedoluha *et al.*, 2002]. The latter paper also showed significant variation in the rehydration, as also shown in the MLS data.

Irreversible dehydration implies that ice sedimentation must have been happening, as the water vapour is permanently removed when the ice particles fall to lower levels. Particles of different sizes will sediment at different speed, experiencing multiple cycles of sedimentation, evaporation and particle formation depending on the temperatures encountered. The average values in Figure 2 are not sufficient to give insight into these processes and more detailed studies, including trajectory analysis to follow temperature history and examination of other datasets to detect ice clouds and to estimate total water, are needed. However, at 360 K the vortex-averaged water vapour shows an increase from the middle of June, when dehydration starts at the upper levels, and lasts for a month until the first signs of dehydration appear at this level. This feature does not seem related to dynamical processes, as it is not shown in the other MLS trace gases, so the increase is likely related to the evaporation of ice particles falling from upper levels.

The horizontal extent of the dehydration is analysed in Figure 3. MO analyses were used to calculate the equivalent latitude (EqL), the latitude enclosing the same area as a given PV contour. The plot shows clear differences in the horizontal extent of the dehydrated areas for the 2004 and 2005 coincident winter periods. These differences are again qualitatively consistent with the areas enclosed for the given range of temperatures, with larger cold areas for the 2005 winter. For this winter, at the beginning of July there is good agreement in time between the development of areas with water vapour values smaller than 3 ppmv and temperatures lower than 190 K. The disappearance of these cold areas in the beginning of September is not followed by the disappearance of the very dehydrated areas. Some gradual recovery is observed during the following months, but areas dehydrated up to 3 ppmv survive till December. This is again an indication of permanent dehydration.

### 3. The 2004-2005 Arctic Winter

Figure 4 shows the evolution of MLS water vapour and temperature averaged inside the vortex. As documented before [e.g. Nedoluha *et al.*, 2002], temperatures in the Arctic are in general not low enough to produce the extensive dehydration seen in the Antarctic vortex. The temperature field displayed in Figure 4 shows a warmer vortex and no significantly depleted water vapour.

However, the 2004-2005 Arctic winter was the coldest on record in the lower stratosphere, with more days and a larger average region where polar stratospheric clouds could form than observed in any previous northern hemisphere winter [Manney *et al.*, 2006]. Single dehydration events could then be expected, as observed before during cold winters [e.g. Herman *et al.*, 2003]. Difficulties arise as the vortex was also dynamically very active [Manney *et al.*, 2006], making the interpretation of these low values ambiguous. Therefore we also consider the output of the SLIMCAT chemical transport model [Chipperfield,

1999] and reverse trajectory (RT) calculations [e.g. *Manney et al.*, 2000]. MO analyses were used to force SLIMCAT, while NASA’s Global Modeling and Assimilation Office Goddard Earth Observing System (GEOS-4) analyses [*Bloom et al.*, 1995] were used to drive the RT calculations.

After analysing the whole winter, despite the very low temperatures only one possible dehydration event over Spitsbergen was observed at the end of January. This event is shown in Figure 5 with maps of water vapour at 460 K ( $\sim 19$  km) from MLS, the SLIMCAT runs, and the RT calculations. SLIMCAT was sampled at the specific MLS locations, while the RT calculations were initialised with MLS data 12 days prior to each plotted day at the positions of parcels advected back to that day using GEOS-4 winds. The 188 K temperature contours from the GEOS-4 and MO analyses are also overlaid on the MLS and SLIMCAT maps, respectively. Although there are some small differences between the analyses, both identify similar regions of very low temperatures. The low values of water vapour (a drop of  $\sim 0.5$  ppmv with respect to vortex background values) of 25, 26 and 27 January are well correlated with the areas of very low temperatures, extend vertically from  $\sim 340$  to  $\sim 480$  K ( $\sim 12$ -20 km), and are also reproduced by SLIMCAT. In contrast, the RT calculations, showing the advection of the MLS water vapour fields, do not show the depleted water vapour, strongly suggesting that this is not a dynamical feature, but the result of the conversion of water from the gas to the solid phase due to the decrease in temperature. Note that Figure 5 shows another low water vapour event on 29 and 30 January. SLIMCAT also reproduces this event but, contrary to the previous case, the RT calculations also display this feature, showing that the depleted water vapour areas are not related to ice formation but associated with an intrusion of lower latitude air into the vortex. A more detailed study of this intrusion [*Schoeberl et al.*, 2006] relates this event to a filament formed from vortex edge material brought inward and advected inside the vortex.

## 4. Summary

Observations of water vapour and temperature from EOS MLS are used to provide a first look at the dehydration of the 2004 and 2005 polar vortices. The Antarctic winters show the expected dehydration associated with the removal of water from the gas phase under ice-forming temperatures. MLS was not operational yet during the early 2004 winter, but significant differences were found between the late winters, with a 2005 colder winter resulting in a more extensively dehydrated vortex. For the 2005 winter the water vapour reductions started from mid-June, coincident with the decrease in temperatures. The dehydration extended vertically between  $\sim 12$ -21 km. Reductions of up to  $\sim 3$  ppmv in water vapour were recorded a month later. Permanent dehydration was evident between  $\sim 15$ -20 km three months later, when the start of the temperature recovery was not followed by an increase in water vapour. For the 2004 winter the water vapour decrease was smaller and no signature of dehydration was found at  $\sim 20$  km, but only the late winter was observed.

The 2004-2005 Arctic winter was unusually cold, but only one single event of depleted water vapour on 25-27 of January was linked to the likely formation of ice under very low temperatures. RT calculations and the model SLIMCAT demonstrated that this event is consis-



tent with ice formation, and could not have arisen solely from transport processes. For this event, the MLS data show a drop of up to  $\sim 0.5$  ppmv, extending over Spitsbergen between  $\sim 12$ – $20$  km.

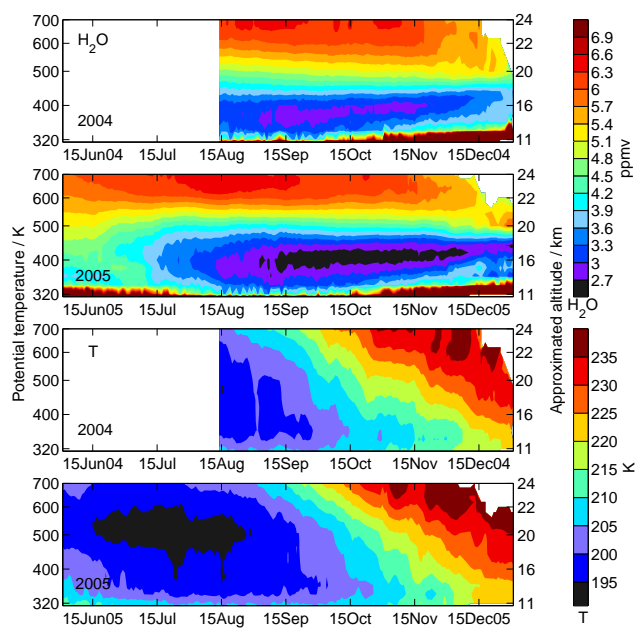
**Acknowledgments.** Thanks to M. P. Chipperfield for developing and sharing the SLIMCAT model, to NASA’s Global Modeling and Assimilation Office for GEOS-4 data, and to the Met Office for their stratospheric assimilations. Work at the School of GeoSciences was done under contract with the Natural Environmental Research Council. Work at the Jet Propulsion Laboratory was done under contract with the National Aeronautics and Space Administration.

## References

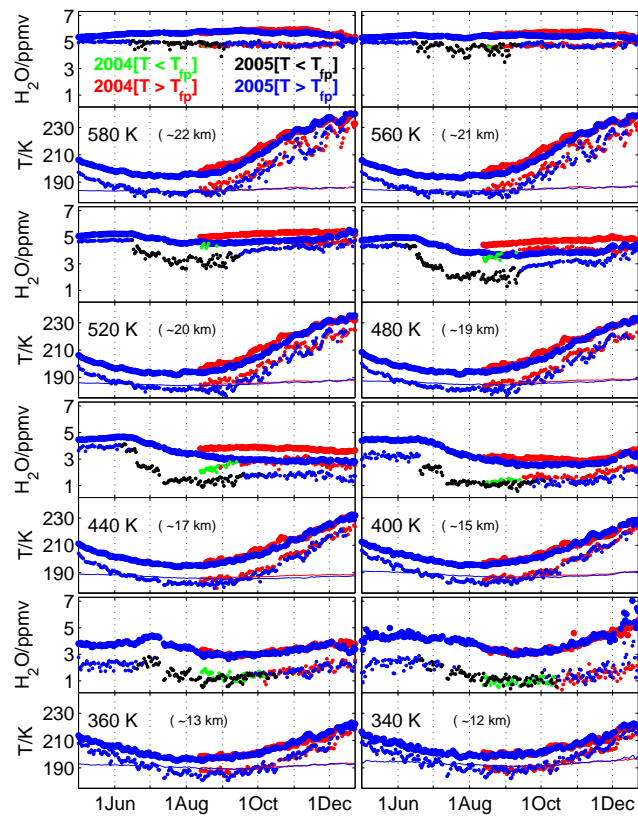
- Bloom, S. C., et al., The Goddard Earth Observing Data Assimilation System, GEOS DAS Version 4.0.3: Documentation and Validation, *Tech. Rep. 104606 V26*, NASA, 1995.
- Chipperfield, M. P., Multiannual simulations with a three-dimensional chemical transport model, *J. Geophys. Res.*, *104*, 1781–1805, 1999.
- Fahey, D. W., et al., Observations of denitrification and dehydration in the winter polar stratosphere, *N*, *344*, 321–324, 1990.
- Froidevaux, L., et al., Early validation analyses of atmospheric profiles from EOS MLS on the Aura satellite, *IEEE Trans. Geosci. Remote Sensing*, *44*, 1106–1121, 2006.
- Herman, R. L., et al., Hydration, dehydration and the total hydrogen budget of the 1999/2000 winter Arctic stratosphere, *J. Geophys. Res.*, *108*, doi:10.1029/2001JD001257, 2003.
- Kelly, K. K., et al., Dehydration in the lower Antarctic stratosphere during late winter and early spring, 1987, *J. Geophys. Res.*, *94*, 11,317–11,357, 1989.
- Manney, G. L., et al., On the motion of air through the stratospheric polar vortex, *J. Atmos. Sci.*, *51*, 2973–2994, 1994.
- Manney, G. L., et al., Lamination and polar vortex development in fall from ATMOS long-lived trace gases observed during November 1994, *J. Geophys. Res.*, *105*, 29,023–29,038, 2000.
- Manney, G. L., et al., EOS MLS observations of ozone loss in the 2004–2005 Arctic winter, *Geophys. Res. Lett.*, *33*, doi:10.1029/2005GL024494, 2006.
- Nedoluha, G. E., R. M. Bevilacqua, and K. W. Hoppel, POAM III measurements of dehydration in the Antarctic and comparison with the Arctic, *J. Geophys. Res.*, *107*, doi:10.1029/2001JD001184, 2002.
- Pan, L. L., et al., Satellite observations of dehydration in the Arctic Polar stratosphere, *Geophys. Res. Lett.*, *29*, doi:10.1029/2001GL014147, 2002.
- Santee, M. L., et al., Polar processing and development of the 2004 Antarctic ozone hole: First results from MLS on Aura, *Geophys. Res. Lett.*, *32*, doi:10.1029/2005GL022582, 2005.
- Schoeberl, M. R., et al., Chemical observations of a polar vortex intrusion, *J. Geophys. Res.*, in press, 2006.
- Stone, E. M., et al., Onset, extent, and duration of dehydration in the Southern Hemisphere polar vortex, *J. Geophys. Res.*, *106*, 22,979–22,989, 2001.
- Waters, J. W., et al., The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura Satellite, *IEEE Trans. Geosci. Remote Sensing*, in press, 2006.

---

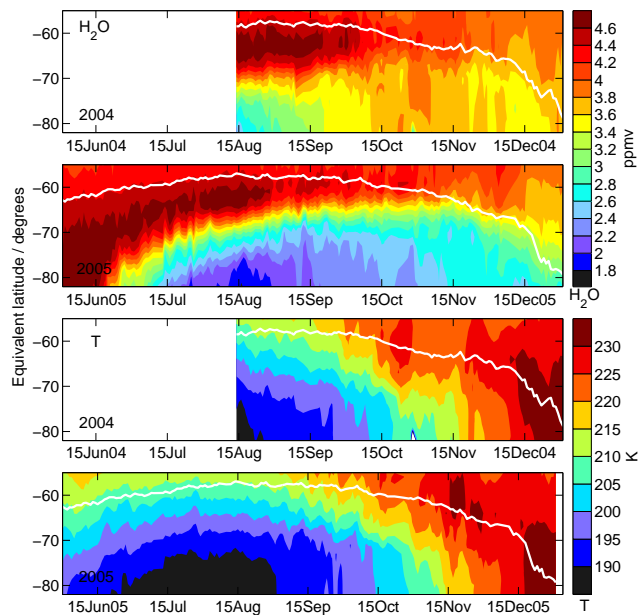
C. Jiménez, School of GeoSciences, The University of Edinburgh Crew Building, Mayfield Road, Edinburgh EH9 3JN, UK (carlos.jimenez@ed.ac.uk)



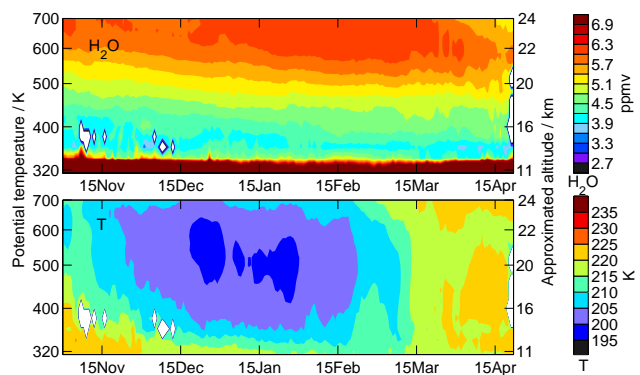
**Figure 1.** Time series of vortex-averaged MLS water vapour and temperature versus potential temperature during the 2004 and 2005 Antarctic winters.



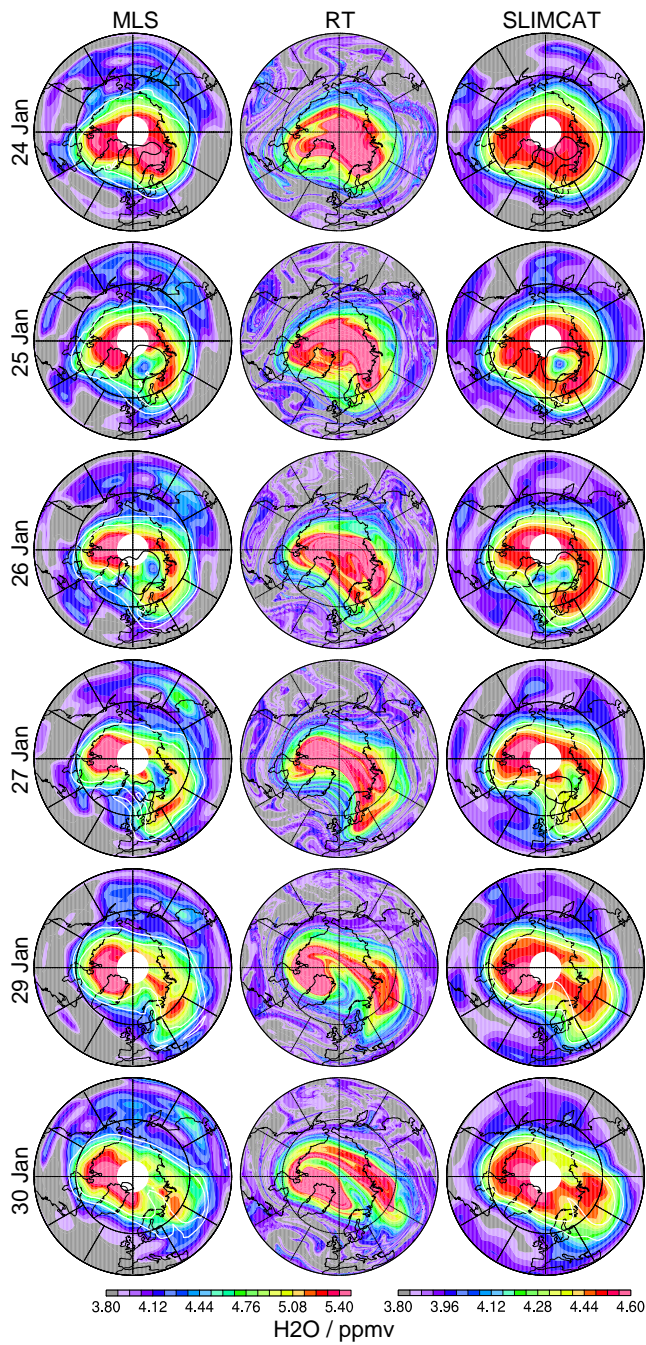
**Figure 2.** Time series of minimum and vortex-averaged MLS water vapour and temperature inside the vortex during the 2004 (red and green) and 2005 (blue and black) Antarctic winters. The average curves are plotted with larger symbols. The continuous horizontal line marks an approximated frost point temperature ( $T_{fp}$ ). The 2004 minimum water vapour values are plotted in red ( $T > T_{fp}$ ) and green ( $T < T_{fp}$ ), the 2005 values in blue ( $T > T_{fp}$ ) and black ( $T < T_{fp}$ ).



**Figure 3.** Time series of water vapour and temperature versus equivalent latitude (EqL) at 440 K ( $\sim 17$  km) during the 2004 and 2005 Antarctic winters. The white contour shows the vortex edge.



**Figure 4.** Time series of vortex-averaged MLS water vapour and temperature versus potential temperature during the 2004-2005 Arctic winter.



**Figure 5.** Maps of water vapour from MLS, SLIMCAT and RT calculations at 460 K (~18 km) for the end of January 2005. A different contour range is used for SLIMCAT, since the initialisation of that model results in a different range of values. The 188 K temperature contour is overlaid in black. Potential vorticity contours (sPV=1.3 and 1.7) are overlaid in white. The potential vorticity and temperature fields for the MLS and SLIMCAT maps are taken from the GEOS-4 and MO analyses, respectively.